**Individual-based model**

The presentation of our individual-based model follows the standard Overview, Design concepts, and Details (ODD) protocol (Grimm *et al.*, 2006, 2020).

**Overview**

***Purpose and patterns***This IBM aims to simulate the reintroduction and movement of reintroduced red deer on Corsica. We validate this model through its ability to replicate patterns observed in Corsican red deer: their home range sizes (measured as the number of unique patches visited in an individual deer’s lifetime) and by comparing habitat preferences of observed deer data to simulated deer data.

***Entities, state variables, and scales***There are three entities present in this IBM: environment patches, deer agents, and deer release site agents.

*Patches* are 1 ha square representations of the landscape of Corsica. These have state variables:

* landcover: Artificial, Agricultural, Forest, Scrub, Bare, Wetland.
* slope: in x units calculated by x method
* distance-to-road: the Euclidean distance to the nearest x type road, in meters.
* n-visits: the number of visits by deer to the patch
* movement-prob: the probability an individual deer moves to the patch

*Deer* are agents representing individual deer. They are split into mature deer (≥ 1 year old) and immature deer (< 1 year old). Deer are characterised by state variables:

* age: the age of the deer (in ticks)
* sex: male or female
* mature: whether they are mature or not
* offspring: whether they have offspring
* mother’s-ID: for immature deer, their mother’s WHO ID
* independence-countdown: a numerical variable to count down in ticks until an immature offspring deer is mature
* release-site-x: the x coordinate of the release site (for released deer) or the home range centre (for birthed deer)
* release-site-y: the y coordinate of the release site (for released deer) or the home range centre (for birthed deer)

*Deer release sites* are agents representing the release sites of individual deer which were originally reintroduced onto Corsica. Their state variables are:

* sex-of-released: the sex of the deer to be released (male/female)
* release-time: the release time in the model (in ticks)

Global variables also present in this IBM include:

* date-time: the simulated date and time (10:00 or 22:00)
* season: whether it is summer or winter
* annual-birth-probability: the probability a deer will give birth in a year
* annual-death-probability: the probability a deer with die in a year
* max-distance: the maximum distance a deer can move in a 12-hour period (one tick)
* focal-deer: the WHO ID of the deer for which patch-level movement-probs are being calculated (see *move-mature*)
* target-patches: a list of patches which are within a deer’s max-distance (see *move-mature*)

date-time and season are used to track whether it is summer or winter for the purpose of modelling deer movement. Summer begins on 15th April, whilst winter begins on 15th October.

***Process overview and scheduling***Each tick represents a 12-hour period, as this is the temporal resolution of the GPS tracking data. During each tick, six sub-models execute in the below order:

1. *deer-release* simulates the initial reintroductions of deer onto Corsica
2. *birth* simulates the birth of deer
3. *move-mature* simulates the movement of mature deer, informed by the SSF outputs
4. *move-immature* simulates the movement of immature deer
5. *death* simulates the death of adult deer and any associated offspring
6. *age* increases the age of all deer by 12 hours

*move-adult* is executed prior to *move-offspring* to ensure offspring follow their mother. In addition, *death* is executed in ID order to ensure mothers die before offspring.

Finally, a *patch-count* procedure is executed by patches to update their n-visits variable, should a deer visit the patch.

**Design Concepts**

***Basic principles*** The basic principle of the IBM is to simulate red deer reintroduction into Corsica. The proximate aim of the IBM is to replicate red deer population dynamics and movement, whilst the ultimate aim is to explore and predict areas of potential human-deer conflict.

***Emergence*** The movement behaviour of deer emerges from the model by being probabilistically determined at the patch-level for each deer based on variables identified in the SSF. Population dynamics also emerge from the model and are determined by probabilistic birth and death rates based on expert, local knowledge.

***Adaptation*** Deer do not adapt

***Fitness*** Deer do not calculate fitness

***Prediction*** Deer do not directly predict the consequences of their decisions.

***Sensing***The patch a deer is located on can sense patches, their distance, and their associated state variables within their maximum step length. This is essential so that patches can calculate the relative probability of each deer moving onto them.

***Interaction*** Deer do not interact beyond immature deer following their mothers (see ***Collectives***)

***Stochasticity*** The next patch an individual deer selects to move to is chosen probabilistically based on the SSF. Whether a deer gives birth or dies is also determined probabilistically based on expert, local knowledge.

***Collectives*** Immature deer follow their mother’s movements and share their location until they mature.

***Observation*** To undertake evaluation, validation, and analysis, outputs were: the lifetime home range sizes of all deer at year 2040, the number of deer (split by mature and immature) and unique patches visited by deer at timepoints 2020, 2025, 2030, 2035, and 2040, and the spatial distribution of n-visit values.

**Details**

***Initialisation*** The model begins on 16th December 2015 at 10:00 – the time of the first deer release. Deer are introduced to the model at release-site locations and times according to their real reintroductions on Corsica (table x).

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| --- | --- | --- | --- | --- | --- |
| Table x: variables characterising the initially reintroduced deer. Sex, their release coordinates, and their release tick are values assigned to state variables of the reintroduced deer in the simulation. | | | | | |
| Sex | Name | Release area | Release coordinates | Date-time of first GPS recording | Release tick |
| M | Roberto | North Corsica | 42.49983 9.07655 | 16/12/2015 10:00 | 0 |
| F | Barbara | North Corsica | 42.49983 9.07655 | 16/12/2015 10:00 | 0 |
| F | Sara | North Corsica | 42.49983 9.07655 | 17/12/2015 22:00 | 3 |
| F | Giulia | Center of Corsica | 42.24787 9.16314 | 16/03/2016 10:00 | 182 |
| M | Dioniggi | Center of Corsica | 42.24787 9.16314 | 16/03/2016 10:00 | 182 |
| M | Lucio | Center of Corsica | 42.24787 9.16314 | 16/03/2016 10:00 | 182 |
| F | Raphaelle | Center of Corsica | 42.24933 9.16592 | 19/03/2016 10:00 | 188 |
| F | Victoria | Center of Corsica | 42.24933 9.16592 | 19/03/2016 10:00 | 188 |
| M | Lisandru | Center of Corsica | 42.24933 9.16592 | 19/03/2016 10:00 | 188 |
| F | Aurelia | Center of Corsica | 42.24933 9.16592 | 19/03/2016 10:00 | 188 |
| F | Romane | Center of Corsica | 42.24933 9.16592 | 19/03/2016 10:00 | 188 |
| F | Mattea | Center of Corsica | 42.24933 9.16592 | 19/03/2016 10:00 | 188 |
| F | Antonia | Center of Corsica | 42.24933 9.16592 | 19/03/2016 10:00 | 188 |
| F | Sabrina | Center of Corsica | 42.24787 9.16314 | 20/03/2016 10:00 | 190 |
| F | Vanina | Center of Corsica | 42.24933 9.16592 | 20/03/2016 22:00 | 191 |
| F | Violetta | South Corsica | 41.88473 9.22153 | 01/04/2016 10:00 | 214 |
| F | Sapara | South Corsica | 41.88473 9.22153 | 01/04/2016 10:00 | 214 |
| F | Lama | South Corsica | 41.88473 9.22153 | 01/04/2016 10:00 | 214 |
| F | Cavallara | South Corsica | 41.88473 9.22153 | 01/04/2016 10:00 | 214 |
| M | Petru | South Corsica | 41.88473 9.22153 | 01/04/2016 10:00 | 214 |
| F | Latonaccia | South Corsica | 41.88473 9.22153 | 01/04/2016 10:00 | 214 |
| F | Luvana | South Corsica | 41.88473 9.22153 | 01/04/2016 10:00 | 214 |
| F | Chisaccia | South Corsica | 41.88473 9.22153 | 01/04/2016 10:00 | 214 |
| F | Lia | Center of Corsica | 42.26662 9.17083 | 22/02/2018 10:00 | 1598 |
| F | Stella | Center of Corsica | 42.26662 9.17083 | 08/12/2018 10:00 | 2176 |
| M | Banditu | North Corsica | 42.47735 9.18355 | 12/04/2019 10:00 | 2426 |

***Input*** All input variables dictating deer movement are presented in table x (SSF output). Annual birth and survival probabilities were 65% and 97%, respectively, and were based on expert opinion. The max lifespan was 14 years (Pérez-Barbería, Carranza and Sánchez-Prieto, 2015). The max distance a deer can move in a 12-hour tick is 2.60km, obtained from analysing the raw GPS outputs and selecting the 99.9 percentile step-length.

***Sub-models*** The below sub-models are executed to simulate deer reintroduction, birth, movement, death, and aging.

*deer-release* This simulates the initial reintroductions of deer onto Corsica. For each release site, if the current time is equal to the release site’s release time, the release site will produce a single mature deer with no mother or offspring. This deer’s sex will match the sex of the release site (which represents the sex of the real deer released), and their age is assumed to be 731 (i.e., one year old and mature). The release site xy coordinates of the deer will match those of the release site agent.

*birth* For mature female deer with no offspring, a single immature offspring is produced if a random float between 0 – 1 exceeds the probability of not giving birth over 12 hours. This probability to not give birth at the 12-hour timestep is scaled from the annual probability by taking the 730.5th root; 730.5 is the average number of 12-hour steps in a year, assuming an average of 365.25 days in a year.

All offspring start as immature and with a random sex (50:50 male:female). The offspring’s independence-countdown is randomly assigned as either 730 or 731 so that, on average, 730.5 ticks (365.25 days) pass until an immature offspring matures (see *move-immature*). Finally, the mother will set her offspring variable to ‘yes’ to 1) indicate that she has an offspring and cannot reproduce, and 2) allow for the patch-count procedure to correctly record her offspring.

*move-mature* This probabilistically simulates mature deer movement to a new patch. The relative probability for a deer to move from patch x to patch z is given by:

Zi represents the deer- and patch-level variables influencing deer movement as identified in the SSF, whilst βi represents the effect size for each variable. β is determined by sampling from a normal distribution with a mean equal to the effect size and standard deviation equal to the standard error obtained in the SFF (Table x). n represent the total number of patches. The denominator term sums the probabilities of all possible patches a deer could move to and is used to calculate a relative probability for each patch.

This equation is applied to all patches ≤ max-distance from the deer’s current patch, the ‘target-patches’, and updates their movement-prob variable with the output of the above equation. Based on each patch’s movement-prob, a patch is selected which the deer faces and moves towards. To do this, a random float between 0-1 is first generated. One-by-one and in a random order, each target patch’s movement-prob is summed onto a cumulative probability. If a patch’s movement-prob increases the cumulative probability above the random float value, then that patch becomes the selected patch.

Once a patch is selected, the deer agent faces and moves towards it. To allow for the *patch-count* procedure to register that a deer has visited the patches en route to the selected patch, the deer moves forward 100m at a time until the selected patch is reached. Once the deer reaches the selected patch, the movement stops.

*move-immature* This procedure moves immature, offspring deer. Each immature offspring will change their heading to face their mother and jump to her location, as if they have followed her. If the new location is the furthest location the offspring deer has visited from its mother’s release site, then it updates its *release-site-x* and *release-site-y* variables with the new location. This is based on local, expert knowledge that young deer tend to establish territories on the edge of their mother’s home range.

In addition, the individual’s independence-countdown decreases by one. Should this mean the independence-countdown decreases to zero or lower, the immature deer matures. To mature, they set their mother variable as ‘none’ and their mature variable as ‘yes’. Additionally, their mother sets her offspring variable to ‘no’ so that she can now reproduce again.

*Death* Adult deer die due to both intrinsic and extrinsic causes. If deer exceed the max lifespan, they are assumed to die from intrinsic senescence. Should deer not die from intrinsic senescence, then each mature deer is assumed to die from extrinsic causes if a random float between 0 – 1 exceeds the 12-hour survival probability. Like *birth*, the 12-hour survival probability is scaled from the annual survival probability by taking the 730.5th root.

*Age* This ages deer by 12-hours

*Patch-count* This procedure is triggered when a mature deer visits a new patch. The new patch will increase their n-visit variable by one, to record the mature deer visiting the patch. Should the mature deer have an immature offspring, then they increase their n-visit variable by one again, to record both the visit by the mature deer and their immature offspring.